Study of sound quality control of engine noise and its evaluation

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ABSTRACT

Conventional methods to reduce car engine noise are subject to considerable structural variations. It is often impossible to reduce low frequency sound using ordinary passive methods; only active control of the noise provides a universal solution. However, the traditional production concept for car engine sound has changed, from finding a solution to unwanted noise to actual design of a particular sound. While many studies have investigated the development of comfortable car engine sounds, the psychoacoustic effects of the time-varying rates of accelerating engine sounds remain unclear. If loudness is applied to a nonstationary engine acceleration sound, the resulting sound may be interpreted incorrectly. Therefore, we propose a new indicator for nonstationary noise and have applied the proposed indicator to car acceleration sounds. To find the desired sound to act as the engine sound, we investigated the relationship between the car’s harmonic structure and the auditory impression of the engine sound. Additionally, to change the existing sound into the desired car engine sound, we applied the Command filtered-x least mean squares (Fx-LMS) algorithm to actual car interior noise.

Keywords: Active noise control, Command Fx-LMS algorithm, Car noise, Sound quality control

I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

With the continuing advances in digital signal processing technology, active noise control (ANC) technology [1] is receiving attention as a potential noise reduction measure. ANC technology reduces noise by superimposing a sound on a target where the sound has the same amplitude but the opposite phase. ANC technology has a number of advantages. First, ANC technology is effective in the removal of low-frequency noise, which is difficult to reduce using conventional passive reduction methods such as the application of sound-insulating materials, soundproofing materials, or damping materials. Second, ANC technology can be implemented in smaller spaces than conventional passive reduction methods. Therefore, ANC technology is currently used in vehicle interior noise reduction [2], [3]. However, driving a car can be considered a leisure activity [4], and certain reductions in the level of noise can reduce the driving pleasure, the fun of driving, or the ‘sporty’ feeling for the driver. Control of the engine sound thus shifts towards sound design rather than actual noise reduction [5]. This type of sound design has been actively studied by automobile manufacturers [6], [7].

While many studies have investigated the development of comfortable car engine sounds, the psychoacoustic effects of the time-varying rates of accelerating engine sounds remain unclear. Acoustic qualities such as loudness and sharpness are known as psychoacoustic indicators for stationary sound [8]. In the current study, loudness is applied to the engine acceleration sound [9]. However, if loudness is applied to a nonstationary sound, it may be interpreted incorrectly. Therefore, we proposed a new indicator for nonstationary sound [10].

In this study, we have first applied this new indicator to car acceleration sound. Recently, time-varying loudness was proposed as an indicator for nonstationary noise [11]. We have thus compared the new indicator to time-varying loudness for car acceleration sounds. Second, to find the desired sound to act as
the engine sound, we have investigated the relationship between the harmonic structure and the auditory impression of engine sound. In addition, to change the existing sound into the desired car engine sound, we applied the Command filtered-x least mean squares (Fx-LMS) algorithm [12] to actual car interior noise.

2. Study of sound quality evaluation

2.1 Experimental method

The vehicle used in this study was a left-hand drive sedan vehicle with a four-cylinder four-cycle engine. The interior and intake noises were recorded using a microphone at a sampling frequency of 6000 Hz. The driving conditions were acceleration in third gear with a wide open throttle from 1000 to 6000 rpm. Figure 1 shows a spectrogram of the intake noise.

Figure 1 – Spectrogram of intake noise

Figure 2 – Long-term loudness of car noise
Table 1 – Loudness of car noise

<table>
<thead>
<tr>
<th>Subject</th>
<th>Loudness [sone]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject(1-1)</td>
<td>9.2142</td>
</tr>
<tr>
<td>Subject(1-2)</td>
<td>11.1301</td>
</tr>
<tr>
<td>Subject(1-3)</td>
<td>6.8493</td>
</tr>
</tbody>
</table>

Table 1 shows the loudness applied to each Subject. Figure 2 shows the time-varying loudness applied to each Subject. Subject (1-1) is the intake noise. Subject (1-2) is approximately 1.5 times the rate of frequency variation with time of Subject (1-1). Subject (1-3) is approximately 0.67 times the rate of frequency variation with time of Subject (1-1). As the rate of frequency variation with time (Hz/s) increases, then the loudness value also increases. Additionally, as the rate of frequency variation with time increases, then the slope of the time-varying loudness also increases. Therefore, there is a correlation between the rate of frequency variation with time and the time-varying loudness. The reason for this is that the energy per unit time is different for each subject. This indicates that the loudness may be interpreted incorrectly if it is applied to a nonstationary sound.

Figure 3 – Correlation of subjective evaluation with rate of frequency variation with time

The semantic differential technique is then applied to each subject. Figure 3 shows the correlation of the subjective evaluation with the rate of frequency variation with time. The car acceleration sound is classified with respect to four factors: powerful, metallic, luxurious and quiet. As the rate of frequency variation with time increases, then the sporty feeling for the driver also increases. Therefore, there is a positive correlation between the rate of frequency variation with time and the sporty feeling.

Figure 4 – Correlation of subjective evaluation with loudness variation rate with time
Figure 4 shows the correlation of the subjective evaluation with the loudness variation rate with time. However, the rate of frequency variation with time causes the loudness variation with time. It is therefore important to consider whether we should use an analysis based on the rate of loudness variation with time or that based on the rate of frequency variation with time.

3. Study of impression variation of car sound quality

The previous section focused on the frequency variations of car engine sound. In this section, we focus on the variation of the order components of car engine sound to study the impression variation of car sound quality. Car engine sound can be divided into full-order components and half-order components. Engine sounds originating from full-order components are known to feel comfortable. In contrast, half-order components are subject to noise control because they are unpleasant sounds. The relationship between the harmonic structure and the auditory impression of the engine sound remains unclear. To find the sound desired for the engine sound, we have investigated this relationship.

Subject (2-1) of the base stimuli was the intake noise. The driving condition was acceleration in third gear with a wide open throttle from 1000 to 6000 rpm for approximately 20 s. Because Subject (2-1) shows a dip in spectrum power, Subject (2-2) was the spectrum power interpolation of Subject (2-1). Because half-order components are subject to noise control as unpleasant sounds, Subject (2-3) was produced by elimination of a half-harmonic from Subject (2-2). Subject (2-4) was produced by elimination of a second harmonic from Subject (2-2). Subject (2-5) was produced by elimination of the second and a half-harmonic from Subject (2-2).

3.1 Auditory experiment

We carried out auditory experiments using a semantic differential. The stimuli were presented to 20 healthy volunteers, composed of 16 males and 4 females, with ages ranging from 20 to 23 years old. Table 2 shows a fifth stimulus. The participants were asked to determine their preferred sound to create a scaled preference value rated on a scale of −3 to 3 with thirteen adjective pairs.

<table>
<thead>
<tr>
<th>Subject(2-1)</th>
<th>Intake sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject(2-2)</td>
<td>Spectrum interpolation of Subject (2-1)</td>
</tr>
<tr>
<td>Subject(2-3)</td>
<td>Elimination of half-harmonic from Subject (2-2)</td>
</tr>
<tr>
<td>Subject(2-4)</td>
<td>Elimination of 2nd harmonic from Subject (2-2)</td>
</tr>
<tr>
<td>Subject(2-5)</td>
<td>Elimination of half and 2nd harmonics from Subject (2-2)</td>
</tr>
</tbody>
</table>
Figure 5 – Results of auditory evaluation

Figure 5 shows the results of the auditory evaluation. For most of the adjective pairs, subject (2-1) had the lowest score. Subject (2-4) and Subject (2-5) had higher evaluation scores for “high” and “bright”. In addition, these subjects had higher evaluation scores for “sporty” and “sharp”, which indicate sporty feelings. Subject (2-2) and Subject (2-3) had low scores for “high” and “bright”. These subjects also had high scores for “Powerful”. Therefore, these subjects evaluate higher scores for “luxury”.

Figure 6 – Results of data analysis

Figure 6 shows the results of the data analysis. In these results, the sport factor increases the scores of all subjects. Spectrum interpolation and elimination of a half-harmonic and the second harmonic also increase the sport factor score. Spectrum interpolation and elimination of a half-harmonic increase the luxury factor score. However, elimination of the second harmonic reduces the luxury factor score. The reason for this is that the elimination of the second harmonic produces a lighter sound. A half-order in the car engine sound get worse both the sporty feeling and the luxury factor. Additionally, a dip in the spectrum power also decreased the sporty feeling and the luxury factor score. The impression of the car engine sound was improved by adjusting the spectrum power level. Elimination of the second-order component of the car engine sound also improved the sporty feeling. Therefore, the sporty feeling of the sound can be improved using active noise control.
4. Study of automation of sound quality control

In the previous section, the sound quality was controlled based on heuristics. In this section, the sound quality is controlled automatically based on active control.

4.1 Command Fx-LMS algorithm [12]

The Command Fx-LMS (CMDFX-LMS) algorithm was proposed based on the filtered-x LMS algorithm for sound quality control. Figure 7 shows a block diagram of the CMDFX-LMS algorithm. $W(n)$ is the control filter, $G(z)$ denotes the response of the physical plant, and $\hat{G}(z)$ represents the internal model of the plant.

![Block diagram of the Command Fx-LMS algorithm](image)

4.2 Study of use on actual sound

In recent years, automobile manufacturers have tried to portray the intake noise in a car as a sound with a sense of sportiness. Therefore, the control signal $c(n)$ is the intake sound. This means that the control approach is based on control of the interior noise in the intake sound, with the aim of increasing the sporty feeling for the driver. The reference signal $x(n)$ is the intake sound. The disturbance signal $d(n)$ is the interior sound. The driving conditions adopted were acceleration in third gear with a wide open throttle from 1000 to 6000 rpm over approximately 20 s.

![Controlled interior noise](image)

Figure 8 shows the controlled interior noise characteristics. When compared with the interior noise, the harmonic structure of the controlled interior noise can be observed more clearly. However, the control has not been performed to a sufficient level. One reason for this is that noise disturbances increase as the engine speed increases. Another reason is that the noise frequency also increases.
Figure 9 shows the differences between the control signal $c(n)$ and the controlled interior noise $e(n)$. As the engine speed increases, the errors also increase. At speeds of more than 5000 rpm, the errors increase remarkably. As a result, the necessity to provide countermeasures to address the disturbance is indicated.

CONCLUSIONS

Loudness and time-varying loudness properties were applied to car acceleration sounds. When the rate of frequency variation with time (Hz/s) increased, then the values of the loudness and the slope of the time-varying loudness characteristic also increased. Therefore, the results for application of both the loudness and the time-varying loudness changed with the time-varying frequency. We used the time-varying frequency to investigate the relationship between time variation and auditory impression in the acoustic order components. We also used time-varying loudness to investigate the relationship between magnitude variation and auditory impression in the order components. However, it is important to consider whether the analysis used in each case should be based on the rate of loudness variation with time or the rate of frequency variation with time. Change by one half-order and a dip in the power of the car engine sound spectrum produce feelings of sportiness and luxury. Elimination of the second-order component of the car engine sound also improved the sporty feeling. The harmonic structure of the car interior noise can be observed more clearly when controlled by the CMD-FXLMS algorithm. However, the overall control performance is insufficient. This insufficiency occurs because the disturbances increase when the engine speed increases and because the noise frequency also increases. As the engine speed increases, the errors increase, and at speeds of more than 5000 rpm, these errors increase remarkably. As a result, the necessity to provide countermeasures to address the disturbance caused is indicated.

In future work, the above findings will be adapted to actual sound design in vehicles, and will be used in quality control techniques to improve robustness to disturbances.

REFERENCES